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Mach 6.5 Air Induction System Design for the Beta II Two-Stage-to-Orbit Booster Vehicle

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MACH 6.5 AIR INDUCTION SYSTEM DESIGN FOR THE BETA II TWO-STAGE-TO-ORBIT BOOSTER VEHICLE

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ABSTRACT

A preliminary, two-dimensional, mixed compression air induction system is designed for the Beta II Two-Stage-to-Orbit booster vehicle to minimize installation losses and efficiently deliver the required airflow. Design concepts, such as an external isentropic compression ramp and a bypass system, are developed and evaluated for performance benefits. The design is optimized by maximizing installed propulsion/vehicle system performance, and the resulting system design operating characteristics and performance are presented. The air induction system design has significantly lower transonic drag than similar designs, and only requires approximately 1/3 of the bleed extraction. In addition, the design efficiently provides the integrated system required airflow, while maintaining adequate levels of total pressure recovery. The excellent performance of this highly integrated air induction system is essential for the successful completion of the Beta II booster vehicle mission.

NOMENCLATURE

A_0	inlet operating streamtube area (ft^2)
A_0/A_c	inlet operating to capture area ratio (mass flow ratio)
A_c	inlet capture area (ft^2)
C_D	drag coefficient [drag/(q x A_c)]
q	freestream dynamic pressure (lb/ft^2)
M_0	freestream Mach number
P_{t_2}/P_{t_0}	inlet total pressure recovery
TBE	Turbine Bypass Engine
W_{2c}	airflow corrected to engine face conditions (lb/s)

INTRODUCTION

During the past year, NASA has sponsored efforts to study and define an efficient airbreathing propulsion system with a maximum Mach number of 6.5 for the booster stage of the Beta II[1] Two-Stage-to-Orbit (TSTO) vehicle, shown in Figure 1. A significant element of this study was the preliminary design of an air induction system, including definition of the inlet and extraction systems, such as bleed and bypass.

The main goal of this study was to design a mixed compression air induction system that accounts for, and minimizes, installation losses while efficiently delivering the required airflow throughout the flight regime. The major design ground rules required integration with a two-dimensional, podded nacelle design, and integration with a Turbine Bypass Engine (TBE) turbojet/ramjet engine configuration[2], shown in Figures 2 and 3, respectively. The engine configuration consisted of a separate ramjet duct over the duct containing the four TBEs. In this case, twin podded nacelles, as opposed to a NASP type integrated propulsion system, were required for the

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Beta II concept to accommodate the bottom mounted orbiter vehicle staging system[1].

The challenges involved in a Mach 6.5 air induction system design include satisfying airflow requirements and reducing transonic drag while maintaining adequate total pressure recovery. These challenges, and the significant design characteristics developed to meet these challenges, are among the topics discussed in detail in this paper. The emphasis of the following discussion focusses on the design procedure, description and performance of the air induction system.

AIR INDUCTION SYSTEM DESIGN PROCEDURE

A detailed analytical procedure was formulated and executed to complete the preliminary design of the Mach 6.5 Beta II air induction system. The air induction system, consisting of the inlet, bleed and bypass systems, was designed to integrate efficiently with the Beta II propulsion system and to minimize installation effects. The procedure was to evaluate and define the TBE/ramjet engine airflow requirements[2], and define the inlet geometry required to efficiently satisfy the airflow at all flight conditions. Next, the inlet bleed and bypass systems were designed, and iterations were made to determine the inlet/bypass system characteristics that yield minimum air induction system drag with adequate total pressure recovery. As a result of these iterations, the inlet capture area and variable geometry were defined to maximize system performance. Singular aspects of the design, such as total pressure recovery, were not maximized individually.

Various calculations and computational procedures were performed to develop the inlet design. Program INLETMOC[3] used a method-of-characteristics procedure to assist in defining external and internal duct flow characteristics. Initially, this code was used to develop the two-dimensional geometry that defined the ramp geometry, cowl geometry and location, and flowpath for efficient external and internal compression. In addition, Program INLETMOC provided a non-viscous, initial estimate of inlet total pressure recovery at all flight conditions.

Program IPAC, which is a NASA-LeRC in-house code, was then executed to evaluate the viscous inlet performance. IPAC is a code that calculates inlet overall performance by using one-dimensional analytical techniques assembled from references 5-10. A more detailed procedural explanation can be found in reference 11. Performance calculations output from Program IPAC included inlet airflow capability, total pressure recovery and drag coefficient. All drag coefficient information presented is referenced to capture area (A_c).

The bleed system requirements were defined, and the inlet geometry was modified to satisfy the increased airflow demand. The bleed system performance for this configuration was approximated entirely from references 7, 12 and 13, and is described later.

The bypass system requirements were defined iteratively by stepwise increasing bypass airflow, modifying inlet geometry, and evaluating performance. When either the minimum of the sum of the inlet spillage and inlet bypass drags was attained, or the bypass duct maximum airflow was attained, the iteration was terminated. Program RAMSCRAM[4], which is a one-dimensional ramjet simulation code, was executed to define the bypass duct maximum airflow. Program RAMSCRAM calculations were based on duct characteristics, such as diameter and viscous pressure loss estimates.

Although the bypass system weight was not estimated and factored into the system performance, it should be noted that the Beta II vehicle[1] can physically accommodate the bypass system modeled, and will be discussed later.

As a result of the above procedure, the air induction system was defined and provided the required airflow at minimum drag levels for this configuration.

RESULTS

The results discussed below are separated into sections describing the air induction system design and geometry, airflow performance, total pressure recovery performance and drag performance.

Air Induction System Design

The air induction system design is shown in Figure 4, and consists of an inlet, subsonic diffuser, bleed system and bypass system. The inlet is a Mach 6.5, two-dimensional, two ramp, variable geometry, mixed compression system with a fixed capture area of 189.5 ft^2. The first ramp is straight and has variable geometry with angle vertex about the leading edge. The first ramp angle is set to 10 degrees at the design condition to minimize system length (weight) while providing adequate total pressure recovery performance. The second ramp is based on an innovative external compression concept detailed in reference 12, and effectively applies a traditionally internal compression scheme to an external surface. In summary, the second ramp is actuated such that it can change shape along the entire length of its surface, much like some wind tunnel designs. The shape is varied at each flight condition such that the flow is isentropically compressed, thus eliminating oblique shock waves and the corresponding total pressure losses and boundary layer interactions. External compression supersonic flow viscous losses are estimated at 5% for all flight conditions based on reference 5 and 7 methods. The inlet ramp geometry is detailed in Table 1 for all flight conditions. Additional weight due to the isentropic compression ramp mechanism was not estimated and factored into system performance.

The inlet cowl is located for shock-on-lip operation at the design condition, has an initial angle of zero degrees and is also shown in Figure 4. The cowl lip reflected oblique shock is cancelled at the shoulder formed by the second ramp and the inlet throat.

The inlet throat is common to both ducts, and operates at a throat Mach number of 1.7 at the design condition. The inlet throat normal shock becomes established at a freestream Mach number (M_0) of 2.0, and the inlet operates supercritically (started) from M_0 2.0 to 6.5. Below a M_0 of 2.0, the normal shock resides just forward of the cowl lip, and the inlet operates subcritically, or unstarted.

The flow is split to the separate ducts in the subsonic diffuser and diffused a maximum of 20 degrees, thus minimizing flow separation. Total pressure recovery diffusion losses are estimated at 2% for all flight conditions based on reference 4 and 5 subsonic diffusion performance models.

The inlet is equipped with a high pressure bleed system designed to reduce or prevent shock/boundary layer interactions with a minimum of bleed flow, and is shown in Figure 5. The forward bleed section is located along the isentropic compression ramp, and is designed as a series of porous holes. A sliding plate mechanism is located inside the ramp such that only the segment of holes aft of the cowl lip oblique shock/ramp surface intersection point are activated at all flight conditions. At the design Mach number, bleed is extracted at the shoulder formed by the second ramp and inlet throat. As the oblique shock intersection point with the ramp moves forward with decreasing vehicle supersonic Mach number, bleed is extracted along the second ramp from the shock/ramp intersection point to the inlet throat. Porous holes, as opposed to a single bleed slot allow for convenient implementation of this type of system. The aft section of the bleed system incorporates a bleed slot centered about the throat normal shock. The bleed location is chosen for maximum performance, as described in reference 13. In addition, a bleed slot, as opposed to porous holes, is chosen in this case due to superior total pressure recovery performance and convenient integration. Bleed system flow percentages are estimated from reference 12, and bleed system total pressure recoveries are estimated from reference 7. Table 2 summarizes the bleed system performance.

Bleed flow percentage of total inlet airflow is estimated at only 5.5% at the design condition, which is approximately 1/3 the bleed flow requirement of previous hypersonic, two-dimensional inlet designs[12]. The difference is because the external flow boundary layer is not subjected to severe adverse pressure gradients during isentropic compression, and therefore, bleed is not required during external compression of the flow. Therefore, any weight increase due to the isentropic ramp mechanism is offset considerably by elimination of an external compression surface bleed system.

The inlet bypass system is incorporated into the design to bypass additional inlet airflow capability, thus reducing inlet spillage drag. Excess fuselage volume vacated due to reduced vehicle fuel storage requirements[1] allowed for an attractive location for the bypass duct and made incorporation of the system feasible. The bypass system, shown in Figure 5, is integrated with the ramjet duct via an S-duct located forward of the ramjet burner. The flow is ducted through the vehicle fuselage and ported out the vehicle aft end via a convergent nozzle.

The bypass system is modeled using the RAMSCRAM[4] code, which generates flow characteristics for one-dimensional, steady-state flow. The bypass duct is 6 feet in diameter and has a maximum flow capability of approximately 1300 lb/s of corrected airflow. Entrance conditions to the S-duct are input as the inlet diffuser exit conditions, which represents the conditions just prior to the ramjet combustion chamber. The bypass system losses include a 2% total pressure loss at all flight conditions due to S-duct flow turning, as estimated using the methods of reference 5. Also, a 5% total pressure loss at all flight conditions is estimated using reference 7 methods to represent duct length viscous losses. Finally, RAMSCRAM computes the convergent nozzle drag, flow and thrust coefficients for each flight condition. Bypass drag was consistently greater than bypass thrust at all flight conditions, and the results are shown in Table 3.

The criteria used to bypass system airflow is to bypass flow until either the sum of inlet spillage and bypass drag is minimized, or inlet bypass duct maximum flow is achieved. Transonically, the system bypasses the maximum amount of airflow (1300 lb/s), and this represents 28% of the total air induction system operating airflow at that condition. Because the system airflow capture capability is so significant transonically, some flow is spilled even after TBE, ramjet, bleed and bypass airflow requirements are met. Therefore, transonic inlet spillage drag is still present, although it is significantly reduced. At Mach 0.5, only 2.5% bypass airflow is required to minimize the sum of inlet spillage and bypass drag. For the above conditions, bypass flow capability is beneficial because inlet spillage drag decreases faster than inlet bypass drag increases as bypass flow is increased.

At Mach 3.0, no bypass airflow capability is utilized because, at this condition, bypass drag increases faster than inlet spillage drag decreases for all bypass flow ratios from 0 to 30%. Above Mach 3.0, no bypass airflow is required because all available airflow capability is being utilized by the ramjet and bleed system, thus spillage drag is essentially zero.

Airflow Performance

Satisfying airflow demands and providing high quality, high performance, low distortion airflow at all flight conditions are primary requirements for this air induction system design. Figures 6 through 8 clearly present the system airflow performance as a function of trajectory flight condition.

Curves representing engine airflow and air induction system airflow, including the inlet, bleed and bypass system components, are shown. The bleed and bypass airflow curves quantify the flow percentages documented in Tables 2 and 3, respectively. As shown in Figure 6, bleed system airflow is zero subsonically, increases gradually to a maximum at Mach 4.0, then decreases gradually to the design condition. Bleed flow characteristics are calculated as the product of bleed flow percentage and air induction system total operating airflow, and the maximum of this product occurs at Mach

4.0. Bypass system airflow is zero below Mach 0.5, peaks at Mach 1.5, and is zero above Mach 3.0.

Inlet airflow is compared with TBE/ramjet engine airflow[2] in Figure 7 to assess airflow matching compatibility and performance. The combination of requirements to maximize propulsion system thrust[2] results in an air induction system design that compromised high supersonic performance to maximize performance transonically. In effect, the design capture area is smaller than that required for engine/inlet airflow matching at the design condition. Therefore, above Mach 3.0, the inlet is physically unable to meet the maximum engine airflow demands. However, below Mach 3.0, with both TBE and ramjet operating, the inlet is capable of satisfying engine airflow requirements. In fact, between Mach 0.5 and 3.0, the inlet spills excess airflow, even with the significant bypass capability.

For completeness, Figure 8 shows the air induction system total mass flow ratio (A_0/A_c) as a function of Mach number. The total mass flow is infinite at Mach 0.0, and is a minimum transonically. A positive change in A_0/A_c is evident at the inlet starting Mach number (M_0 2.0) due to the change in inlet geometry and operation. A significant negative change occurs at Mach 3.0 due to the reduction in required airflow caused by the termination of turbojet operation. Above Mach 3.0, system airflow is provided to the ramjet only.

Total Pressure Recovery Performance

Air induction system efficiency is measured in part by the ability of the system to maintain total pressure. This system provides efficient flow throughout the flight regime, especially considering the compromising nature of the propulsion system/vehicle integration discussed earlier.

Air induction system total pressure recovery (P_{t_2}/P_{t_0}) versus Mach number is presented in Figure 9, and includes oblique shock, normal shock, supersonic external surface friction, subsonic diffusion and low speed sharp lip total pressure recovery losses. At low subsonic speeds, inlet mass flow exceeds 1.0, indicating that the inlet streamtube is larger than the projected capture area. In this case, suction of airflow around the cowl lip causes separation of the flow and, thus, a reduction in total pressure recovery identified as cowl lip loss. Because of the low inlet lip Mach number characteristic of this inlet at these conditions, the lip losses can be estimated at 3-4%, based on the methods of reference 10. Combined with viscous effects, this yields a respectable total pressure recovery of approximately 0.90 at the sea level static flight condition. A peak of 0.931 is reached subsonically, which compares to the reference 12, Mach 6.0 inlet, non-viscous, maximum recovery of 0.95. [Reference 12 includes a Mach 6.0 preliminary inlet design developed with a similar propulsion system integration philosophy as the present design, and thus, provides a reasonable performance comparison.]

Total pressure recovery performance in the supersonic regime exhibits typical trends with small changes subcritically and large changes supercritically. A significant increase in recovery occurs at the inlet starting Mach number (M_0 2.0) due to the ingestion of the normal shock to the inlet throat, and thus, reduction in shock losses. At Mach 3.0, a small recovery increase occurs when the TBEs are shut down and airflow requirements are reduced, thus reducing the strength and pressure loss of the throat normal shock. Above Mach 3.0, the major contributions to inlet total pressure recovery loss are the initial external oblique shock wave from the first ramp, the strong initial internal oblique shock wave generated by the cowl lip, and the throat normal shock wave. As Mach number is increased, the oblique and normal shock waves increase in strength and are responsible for the continuing decrease in P_{t_2}/P_{t_0} with increasing Mach number. At Mach 6.0, a recovery of approximately 0.3 compares poorly to the reference 12 inlet, non-viscous recovery of 0.45. However, the viscous effects, and the inlet design geometry differences, such as design Mach number (6.5 vs 6.0), and centerbody angle (10 vs 7 deg), account for the bulk of the difference in total pressure recovery.

Drag Performance

Air induction system efficiency is also measured as the ability of the system to maintain low drag characteristics. This system provides low drag throughout the flight regime, and exhibits the inherent drag benefits available to integrated designs.

Figure 10 presents the air induction system total drag coefficient, as well as component drag coefficients (inlet, bleed and bypass systems), as a function of flight Mach number. All are referenced to capture area (A_C). Bleed and bypass system drag coefficients account for less than 50% of the total drag coefficient transonically, and nearly all of the drag coefficient at high supersonic Mach numbers. Bypass system drag coefficient is significant between Mach 0.5 and 3.0, and peaks at Mach 1.5, which corresponds with maximum corrected bypass airflow, as shown in Figure 6. Bleed system drag coefficient is zero subsonically, and is insignificant up to Mach 3.0. Bleed system drag coefficient increases with Mach number, which corresponds to increasing bleed flow percentage, as shown in Table 2, and accounts for nearly all of the total air induction system drag coefficient at and above Mach 4.0.

The air induction system total drag coefficient includes inlet spillage, cowl lip suction, bleed and bypass system effects, and does not include friction or pressure drag losses on the external inlet surfaces. Figure 10 shows the significant effect of airflow spillage on inlet drag coefficient in the Mach 0.5 to 3.0 range. Without the bypass system, however, total system drag coefficient would have been 50 to 100% greater. For instance, at Mach 2.0, total system drag coefficient is approximately 0.18, compared to the reference 12 inlet (no bypass system) total drag coefficient of between 0.27 and 0.4, depending on airflow requirements. At Mach 2.0, inlet drag coefficient is reduced due to the inlet start, and is increased at Mach 3.0 due to the airflow reduction caused by termination of turbojet operation.

Supersonically, the air induction system also outperforms more conventionally designed inlets because of the reduced capture area and innovative geometrical ramp arrangement discussed earlier. For example, at Mach 5.0, the reference 12 inlet has a total inlet drag coefficient of approximately 0.1 compared to 0.04 from Figure 10. Above Mach 3.0, inlet drag coefficient decreases with increasing Mach number, because mass flow ratio is increasing toward 1.0, thereby reducing captured streamtube additive (spillage + cowl lip suction) drag. In fact, total system drag coefficient is almost reduced to simply bleed system drag coefficient at and above Mach 4.0.

SUMMARY

A preliminary design study was undertaken to design a two-dimensional, mixed compression air induction system for the Mach 6.5 Beta II Two-Stage-to-Orbit booster vehicle. The main goal was to design a system that accounts for, and minimizes, installation losses while efficiently delivering the required airflow throughout the flight regime. Design concepts, such as an innovative external compression system and a bypass system, were implemented in a highly integrated design to achieve maximum propulsion/vehicle system performance.

A detailed, one-dimensional performance analysis of the air induction system design emphasized the benefits of the integrated design philosophy, the isentropic compression ramp, and the bypass system. The air induction system designed and analyzed, efficiently provides the propulsion system airflow required to successfully achieve the vehicle mission with significantly less bleed flow extraction and spillage drag than similar designs. The pressure recovery and drag coefficient curves exhibit the accepted trends and characteristics of similar designs. In fact, drag coefficient was significantly reduced, and total pressure recovery was approximately the same as similar design performance. Overall, the challenges of satisfying airflow requirements, reducing transonic drag, and providing adequate total pressure recovery in a highly integrated propulsion/vehicle system were successfully overcome with this air induction system design, thus allowing successful completion of the booster vehicle mission.

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		Ramp 1					Ramp 2			
		Origin		End		Theta	Origin		End	
Mach	Altitude (ft)	X (in)	Y (in)	X (in)	Y (in)	(deg)	X (in)	Y (in)	X (in)	Y (in)
6.5	100,000	0	150	321	93	10.0	321	93	509	9
6.0	79,000	0	150	323	96	9.4	323	96	509	11
5.0	72,000	0	150	324	108	7.5	324	108	516	32
4.0	62,000	0	150	324	113	6.5	324	113	519	44
3.05	50,000	0	150	324	110	7.0	324	110	518	36
3.0	50,000	0	150	324	110	7.0	324	110	522	50
2.0	34,000	0	150	324	110	7.0	324	110	530	69
1.95	34,000	0	150	324	110	7.0	324	110	527	71
1.5	21,000	0	150	324	110	7.0	324	110	530	75
0.9	10,000	0	150	323	99	9.0	323	99	527	75
0.5	0	0	150	323	99	9.0	323	99	527	54
0.2	0	0	150	323	99	9.0	323	99	527	51
0.0	0	0	150	323	99	9.0	323	99	527	32

Table 1 - Inlet first and second ramp geometry

Mach	Altitude (ft)	Bleed Flow (%W2C)	PTBL/PT0	Bleed Drag Coefficient
6.5	100,000	5.5	0.235	0.061
6.0	79,000	5.0	0.235	0.052
5.0	72,000	4.0	0.240	0.037
4.0	62,000	3.0	0.250	0.023
3.05	50,000	2.0	0.270	0.009
3.0	50,000	2.0	0.270	0.011
2.0	34,000	1.0	0.325	0.006
1.95	34,000	1.0	0.325	0.005
1.5	21,000	0.5	0.395	0.002
0.9	10,000	0.0	——	0.000

Table 2 - Bleed system performance

Mach	Altitude (ft)	Bypass Flow (%W2C)	Bypass Drag Coefficient
0.0	0	0.0	0.000
0.5	0	2.5	0.044
0.9	10,000	28.0	0.076
1.5	21,000	28.0	0.100
1.95	34,000	28.0	0.088
2.0	34,000	28.0	0.088
3.0	50,000	0.0	0.000
3.05	50,000	0.0	0.000

Table 3 - Bypass system performance

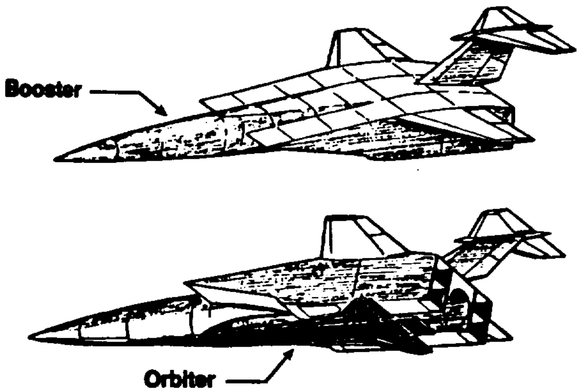

Figure 1 - Beta II Two-Stage-to-Orbit vehicle booster/orbiter configuration

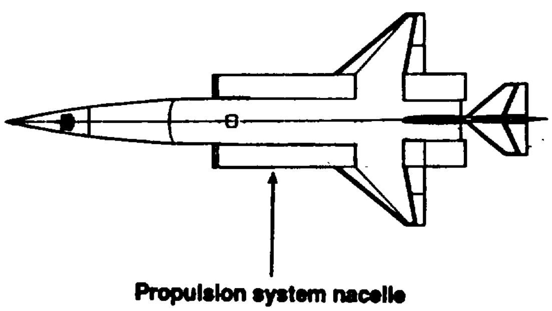

Figure 2 - Beta II booster vehicle propulsion/airframe arrangement

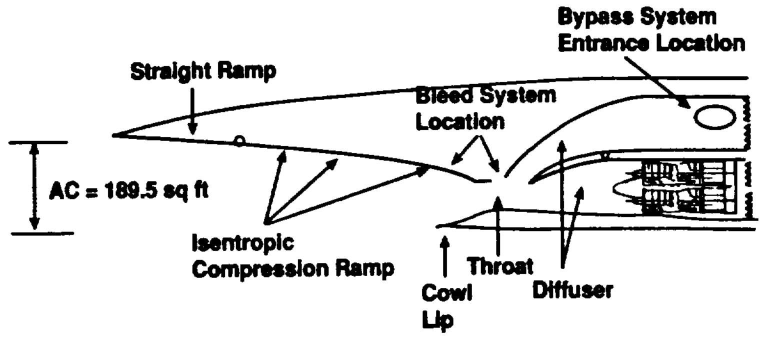

Figure 4 - Air induction system design

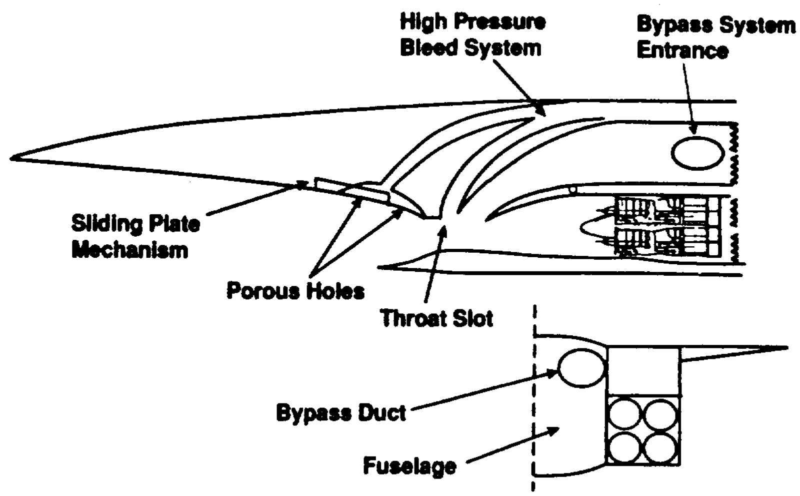

Figure 5 - Bleed and bypass system design details

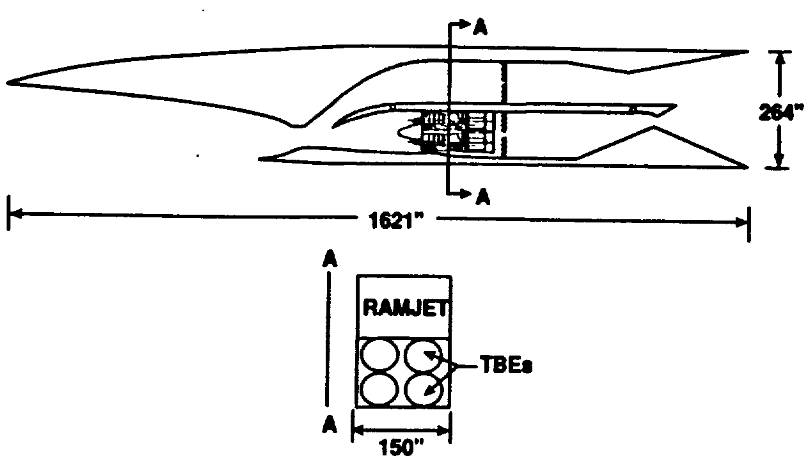

Figure 3 - Two-dimensional, podded propulsion system nacelle configuration

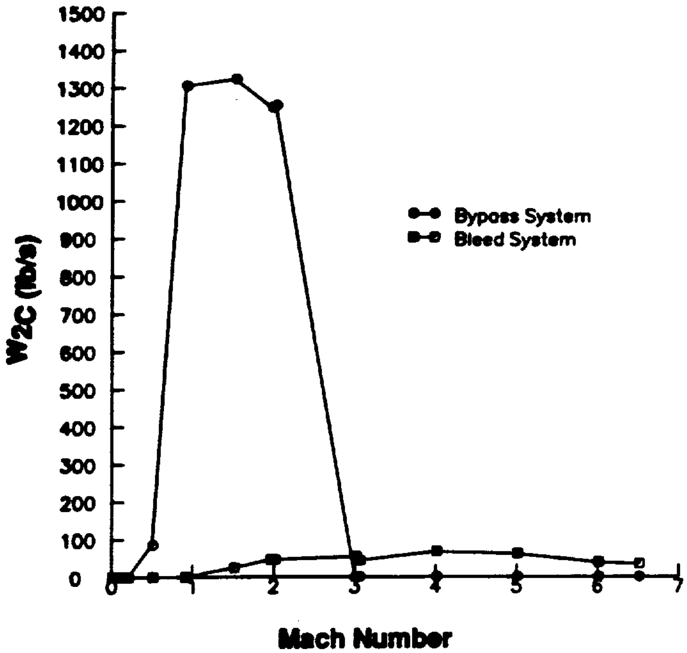

Figure 6 - Bleed and bypass system corrected airflows

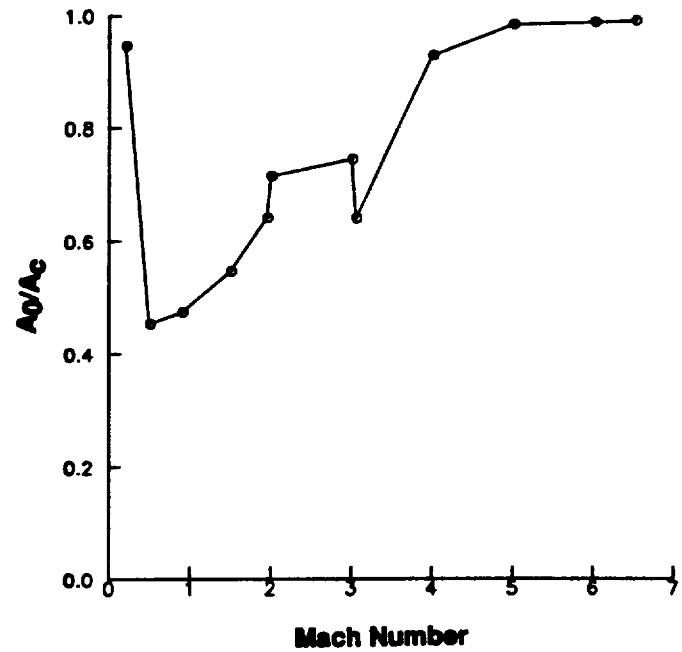

Figure 8 - Air induction system total mass flow ratio

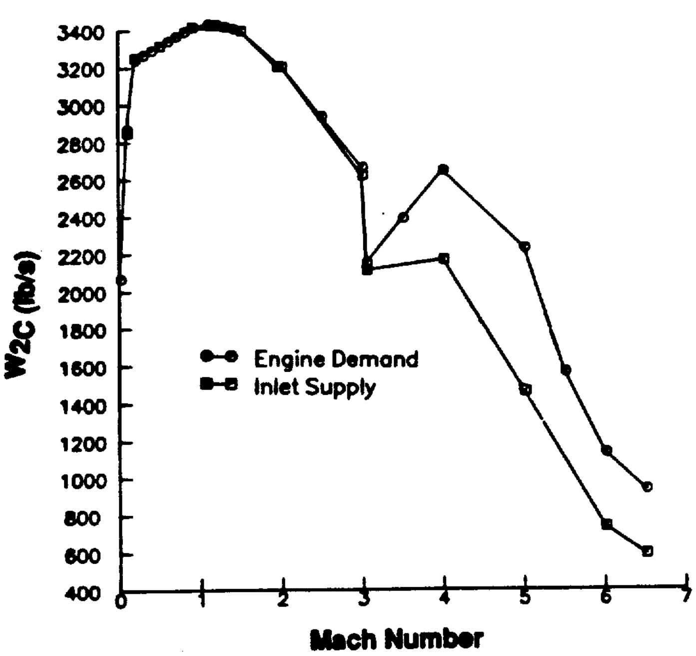

Figure 7 - Inlet/engine corrected airflow comparison

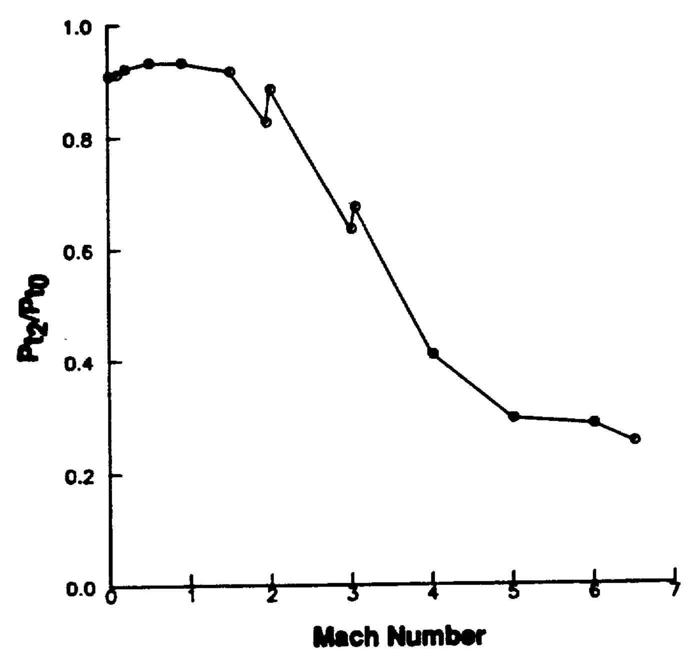

Figure 9 - Air induction system total pressure recovery performance

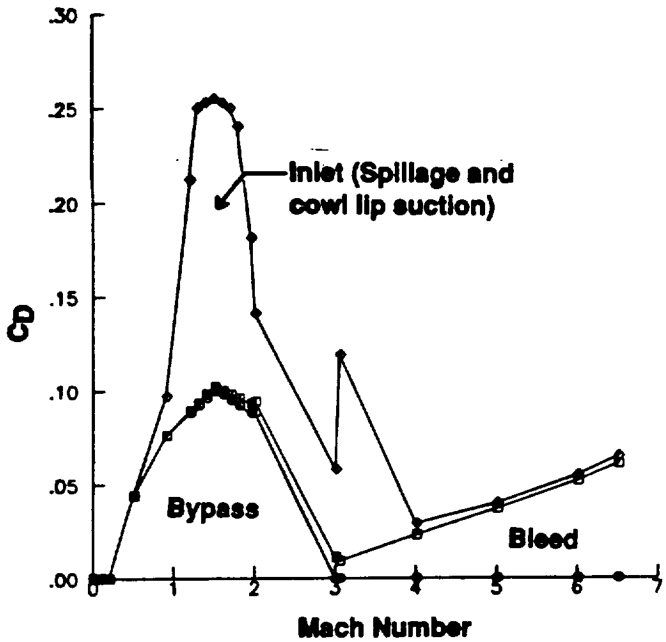

Figure 10 - Air induction system drag coefficient performance

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11. SUPPLEMENTARY NOTES

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13. ABSTRACT ***(Maximum 200 words)***

A preliminary, two-dimensional, mixed compression air induction system is designed for the Beta II Two-Stage-to-Orbit booster vehicle to minimize installation losses and efficiently deliver the required airflow. Design concepts, such as an external isentropic compression ramp and a bypass system, are developed and evaluated for performance benefits. The design is optimized by maximizing installed propulsion/vehicle system performance, and the resulting system design operating characteristics and performance are presented. The air induction system design has significantly lower transonic drag than similar designs, and only requires approximately 1/3 of the bleed extraction. In addition, the design efficiently provides the integrated system required airflow, while maintaining adequate levels of total pressure recovery. The excellent performance of this highly integrated air induction system is essential for the successful completion of the Beta II booster vehicle mission.

14. SUBJECT TERMS

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